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## Enabling Technology for NASA's Europa Orbiter Mission

Edward H. Konefat, Edward C. Litty  
Jet Propulsion Laboratory, California Institute of Technology

Scott K. Voigt, David S. Wright  
Litton Guidance & Controls Systems Division

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## ENABLING TECHNOLOGY FOR NASA'S EUROPA ORBITER MISSION

Edward H. Konefat<sup>\*</sup>  
Edward C. Litty<sup>†</sup>  
Scott K. Voigt<sup>‡</sup>  
David S. Wright<sup>\*\*</sup>

NASA's Europa Orbiter mission ranks as one of the highest priority science missions for planetary exploration with its prospects for finding liquid water. Europa also represents perhaps the most daunting natural space radiation environment for spacecraft equipment encountered so far in the pursuit of planetary science due to the time that must be spent in the inner Jovian system. In order to fulfill the mission science objectives, the combined requirements of enhanced radiation tolerance, high reliability, and long life in a cost-effective, low mass and low power package were flowed down to the attitude control subsystem sensor suite. The Hemispherical Resonator Gyro (HRG) technology, as implemented in Litton's new Scalable Space Inertial Reference Unit (SIRU<sup>TM</sup>) product line, is the unique inertial measurement unit (IMU) available to optimally meet these requirements and has been baselined for missions requiring long life and radiation tolerance, such as Europa Orbiter.

The authors will describe the drivers for the subsystem requirements in the Europa Orbiter mission, in particular the mission criticality of the IMU and the predicted natural space radiation environments that require enabling technologies to be identified. Descriptions of the Europa IMU and the HRG technology are given with emphasis on the inherent radiation hardness in the HRG principle of operation and sensor construction, as well as the steps taken to further harden the sensor electronics.

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<sup>\*</sup> [edward.h.konefat@jpl.nasa.gov](mailto:edward.h.konefat@jpl.nasa.gov), Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA  
<sup>†</sup> [edward.c.litty@jpl.nasa.gov](mailto:edward.c.litty@jpl.nasa.gov), Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA  
<sup>‡</sup> [voigt@littongcs.com](mailto:voigt@littongcs.com), Litton Guidance & Control Systems Division, Goleta, California  
<sup>\*\*</sup> [wrightd@littongcs.com](mailto:wrightd@littongcs.com), Litton Guidance & Control Systems Division, Goleta, California

## INTRODUCTION

The upcoming mission to Jupiter's moon Europa has unique and challenging requirements requiring critical technologies to be identified in order to meet important science objectives. The IMU is a key element of the spacecraft's attitude control subsystem (ACS), typically complemented with a star camera and/or other optical reference sensors. In the case of the Europa Orbiter, the mission includes critical maneuvers, such as the Europa Orbit Insertion (EOI), during which the IMU becomes the sole sensor for propagating the spacecraft attitude. For the EOI burn in particular, the ACS stellar reference unit is not expected to meet performance requirements in the worst case temporal variations. This means that the IMU must be designed to operate reliably through all phases of the mission.

A study program was undertaken to identify an IMU that can withstand the harsh natural space radiation environment and fit within the other constraints and goals for spacecraft components and X2000 bus design. Litton's second-generation HRG space inertial reference unit (Scalable SIRU™) was found to be an enabling technology for the Europa mission. This is very similar to the manner in which the first-generation HRG-based SIRU™ helped to enable the current generation of long-life, 3-axis stabilized, geostationary communication satellites.<sup>1</sup>

## EUROPA ORBITER MISSION<sup>2</sup>

The Europa Orbiter mission will be the first spacecraft to orbit the moon of another planet and could potentially be the first to characterize an ocean of liquid water elsewhere in our Solar System. The Europa Orbiter will launch on a trajectory that starts with a 3-year direct to Jupiter cruise. The cruise phase is followed by Jupiter Orbit Insertion (JOI), after which a 1.5-year tour of Jupiter's satellites uses multiple gravity assist maneuvers to significantly reduce the change in velocity (delta-V) required at EOI. It is the last series of fly-bys at Europa in which the spacecraft is exposed to the severe Jupiter natural space radiation belts. The cost of a minimum delta-V trajectory is an estimated total ionizing dose (TID) of 4 Mrad(Si)\*. Half of this natural space radiation environment is encountered in the 3 months prior to EOI and the other half during 30 days of planned science in orbit about Europa. Figure 1 shows a representative trajectory for purposes of illustrating the Europa fly-bys prior to EOI.<sup>3</sup> The overall mission duration is expected to be over four years.

### Mission Objectives

The scientific interest of this mission is the exploration of Europa and the search for a subsurface ocean of liquid water. The primary science objectives for the Europa Orbiter mission are:

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\* Behind shielding of 100 mils (2.5 mm) of aluminum equivalent.

- Determine the presence or absence of a subsurface ocean
- Characterize the three-dimensional distribution of any subsurface liquid water and the overlying ice layers
- Understand the formation of the surface features, including sites of recent or current activity, and identify candidate sites for future lander missions

Europa Orbiter is to follow the successful Voyager and Galileo missions, which were the last to survey Jupiter's moons. Galileo is currently in Jovian orbit performing science investigations. The Voyager and Galileo data have been used to predict an ocean beneath the icy surface of Europa.<sup>4</sup> An ice-penetrating radar sounder may be used while in orbit around Europa to fulfill the mission objectives for the science community (Figure 2). The science instruments have not been chosen yet for this mission, but it is anticipated that laser altimetry and visible imaging will accompany the radar sounder in satisfying the established primary science objectives.

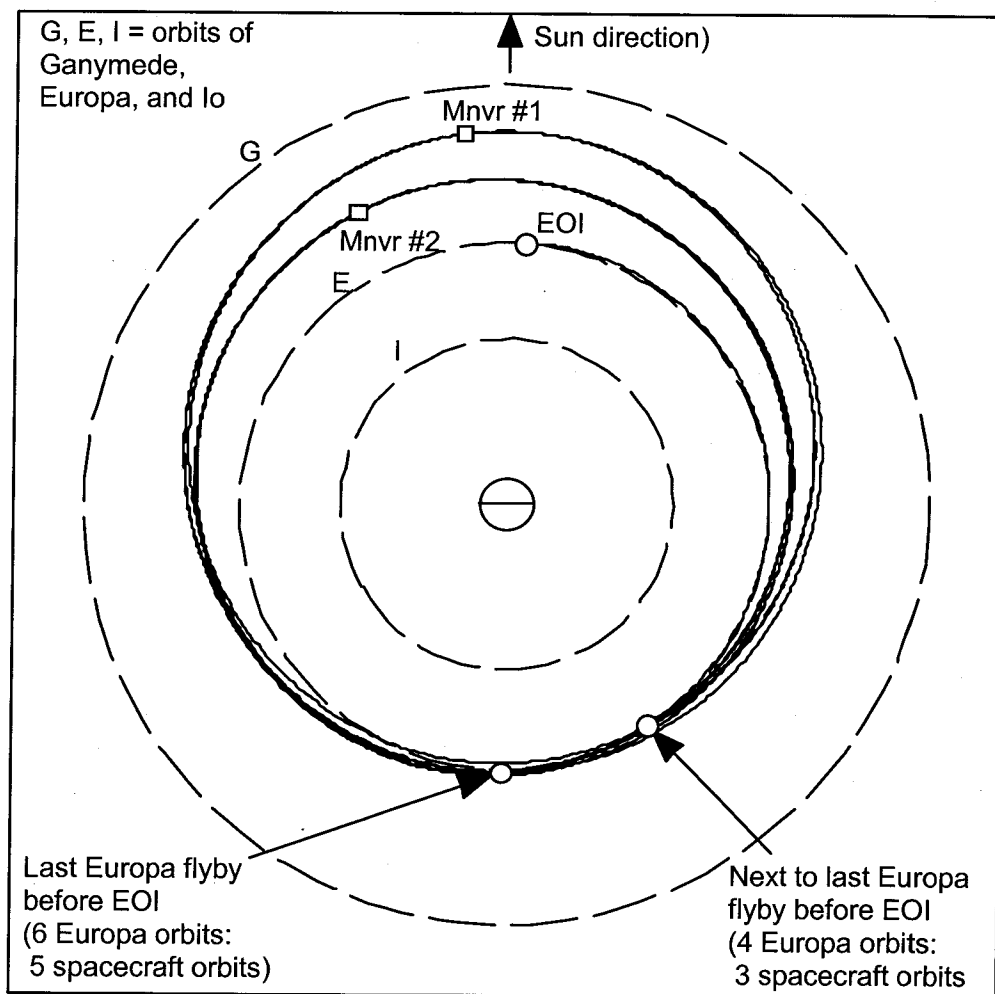
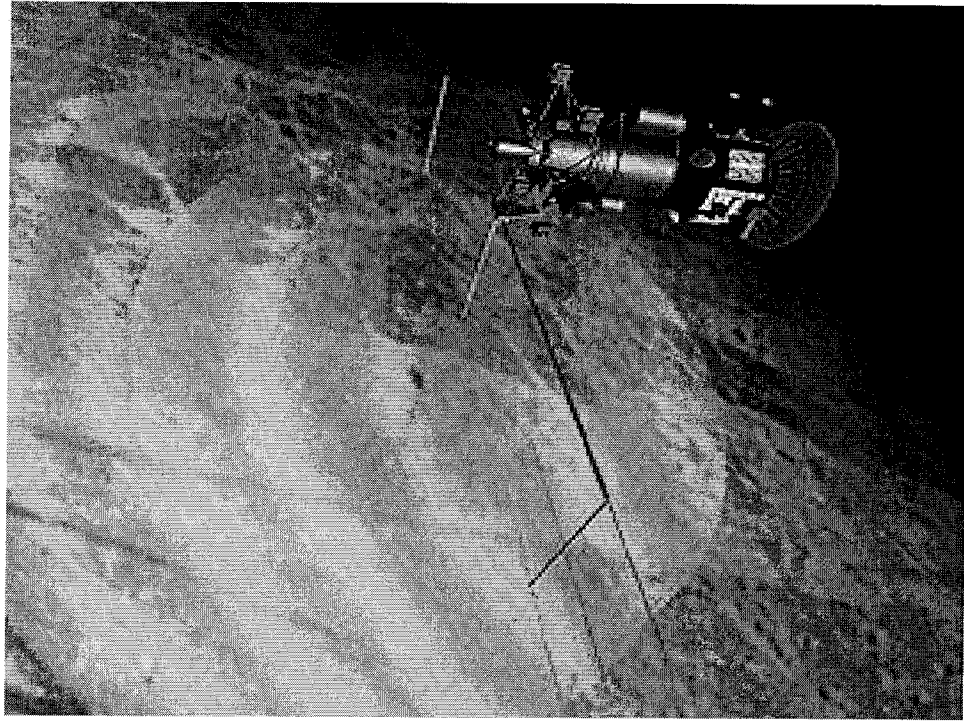


Figure 1. Europa Orbiter Mission Ephemeris (~3 Month "Endgame" Prior to EOI)

The Europa Orbiter will spend significantly more time in the inner natural space radiation belts of Jupiter than either of the Voyager or Galileo spacecraft, enduring many times more TID and single-event effect (SEE) producing particles than its predecessor missions.



**Figure 2. Europa Orbiter's Search for a Liquid Ocean**

### **New Technology from X2000**

The Europa Orbiter will depend on a substantial portion of hardware included on a standard avionics bus being developed under the X2000 program managed by the Jet Propulsion Laboratory. Europa Orbiter is made possible by the advanced technology being developed by the X2000 program.<sup>5</sup> The newly developed X2000 hardware includes a flight computer, low-power data bus, power electronics and other key components. The X2000 System Interface ASIC has multiple ports such as I2C, 1394 and a Mil-Std-1553 bus controller with a modified physical layer. This 1553 port is used for the IMU telemetry and data interface.

The ACS requirements for IMU performance are selected assuming optical sensors will complement the spacecraft attitude estimate and thus the ACS does not require a precision-pointing IMU for the nominal mission. In the case of the Europa Orbiter mission, the IMU takes a more critical role during maneuvers within the extreme

natural space radiation environment. For this reason, a radiation-hard, precision-pointing IMU is essential to the success of the Europa mission.

The X2000 bus architecture and accompanying software will be fully developed on the Europa Orbiter project. The main elements of the spacecraft avionics and the software have been planned for the Solar Probe mission and proposed for use on a Pluto-Kuiper Express mission. The Litton IMU that is the subject of this paper is also baselined for use on the Solar Probe and Pluto missions, however they are expected to see less than 100 krad(Si)\* associated with Jupiter gravity-assist mission design. While high reliability and long life will be driving requirements for all three missions, the Solar Probe spacecraft is expected to also have unique requirements for rapid reset/turn-on recovery from strict off-Sun pointing limitations. An eventual Pluto mission will most likely have a unique case for low power requirements due to the degradation in the power source capability after a very long cruise phase. Litton's new Scalable SIRU™ is capable of meeting these mission-unique requirements by including < 20 second rapid reset/turn-on capability and < 22 W operating power.

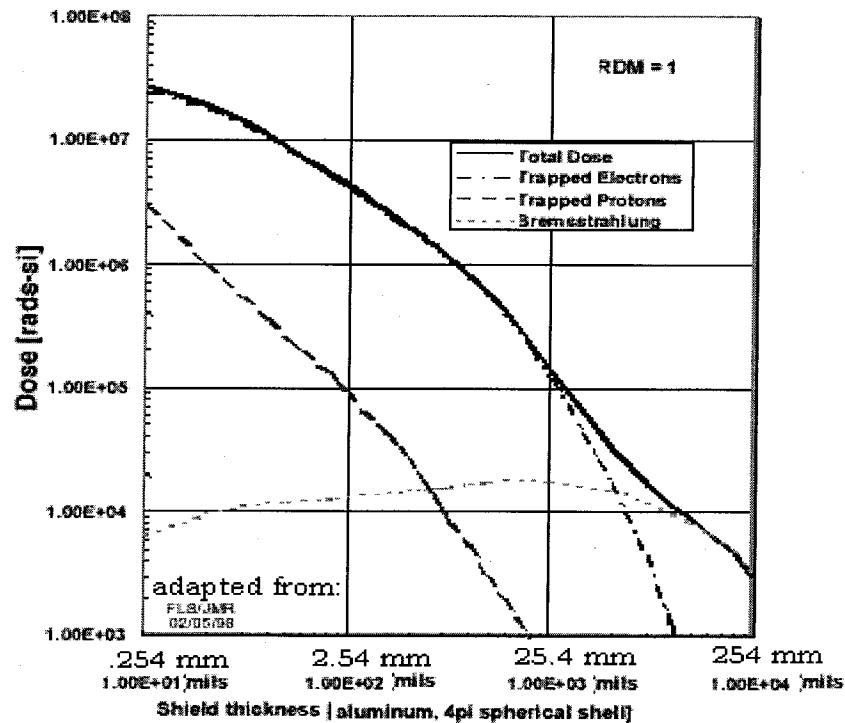


Figure 3. Europa Orbiter Mission Total Ionizing Dose vs. Aluminum Shielding Thickness

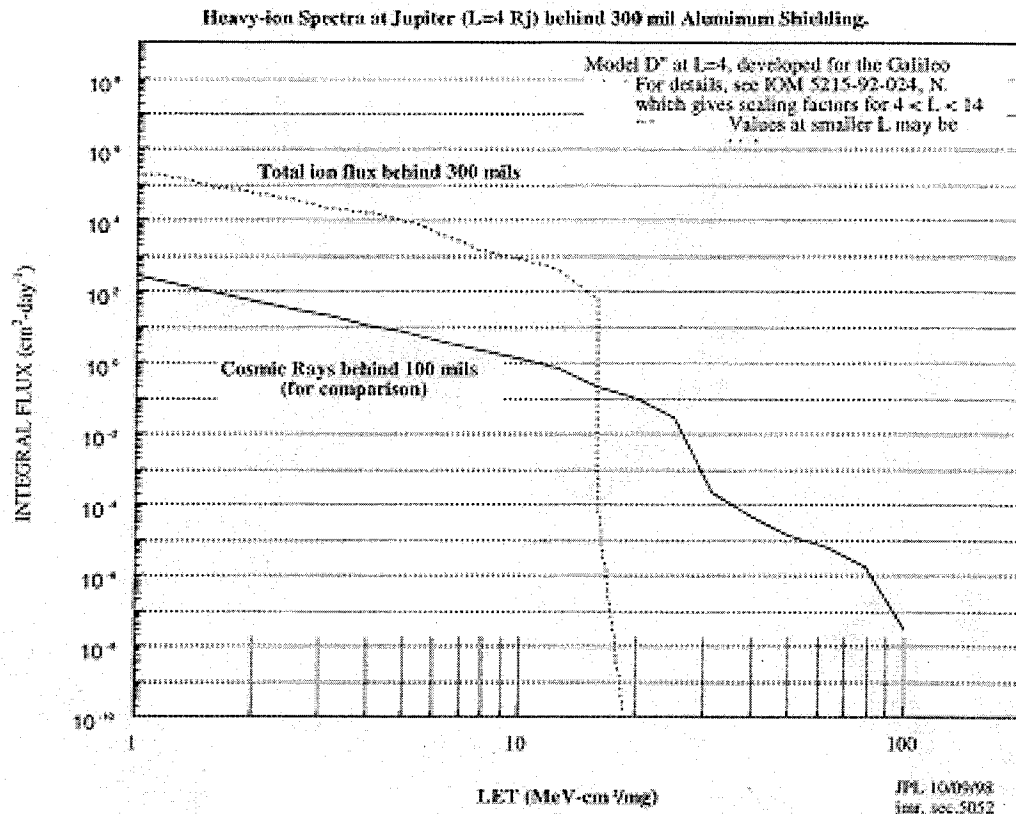
\* Behind shielding of 100 mils (2.5 mm) of aluminum equivalent

## EUROPA NATURAL SPACE ENVIRONMENT

Europa Orbiter spacecraft equipment, such as the IMU, must be developed with consideration for the natural particle radiation environment of the planned mission. This includes the total fluence of electrons and protons from which the total ionizing dose is derived as well as the heavy ions and protons that cause single event effects. For this mission, the natural space radiation environment is dominated by the charged particles trapped in Jupiter's magnetic field.<sup>6</sup> Europa's orbit at 9.4 Jupiter radii is within the intense trapped particle belts surrounding Jupiter.

The most significant impact of the Europa environment on spacecraft equipment design will be from the total ionizing dose. The predicted electron and proton fluence is converted to a total dose figure stated in rads(Si) associated with a thickness of shielding material. This aggregate dose measure indicates the energy absorbed per unit volume of silicon, and can be compared to the tolerance of each semiconductor device used in the equipment at the specified depth of shielding. Figure 3 shows the predicted TID vs. depth of shielding for the Europa Orbiter mission. This data is for aluminum shielding thickness. Other materials, such as much higher density tungsten, will have different shielding effectiveness characteristics. The starting point for the IMU design is approximately 4 Mrad(Si)\* TID, which is ~40 times the typical 15-year geosynchronous Earth orbit TID. Design trade-offs must be made between the added mass of shielding material, desired design margin, and the selection and location of parts, each with measured tolerance to TID levels.

Single event effects are also of concern for Europa Orbiter equipment design. SEEs are produced by heavy ions and protons and are present in the galactic cosmic ray (GCR) background, solar flare events, and Jupiter's natural space radiation belts. Additional shielding often does not substantially reduce the effect of these highest-energy particles that pass through the shielding and deposit charge within components. The SEE environment is described by the predicted flux of particles vs. the particle linear energy transfer (LET). This curve can be compared to each component's threshold LET, or minimum particle LET that can cause a SEE, to determine the probability of a SEE for the individual components. For Europa Orbiter, the GCR background is a constant spectrum of particles throughout the mission, but may be shielded somewhat by Jupiter's magnetic field. The probability of large flare events fluctuates with the Sun's 11-year cycle (assumed to be near the solar minimum during the expected 2004-2008 Europa mission). The Jupiter natural space radiation belts harbor heavy ions whose flux will dominate the SEE environment in the latter part of the Europa mission. SEEs can lead to an "upset" of the device or circuit, but in the most severe cases can cause a "latchup" leading to destructive burnout of the component. Some of the effects can be mitigated by good circuit design principles; however, parts with low thresholds for latchup must be replaced with higher-grade components. The equipment design must be essentially latchup free and meet requirements for very low probability of single event upsets (SEUs). The predicted inner Jovian SEE environment is shown in Figure 4.



**Figure 4. Europa Orbiter Mission Single Event Effects Environment (Heavy Ions and Cosmic Rays at Jupiter)**

## **Component Assessment and Selection for the Space Environment**

A complete assessment was performed on the components of the candidate IMU to verify survivability in high-natural space radiation environments. Replacement components were chosen in some cases based on past performance and tolerance to TID and SEE space environments. Existing data were used to establish a baseline for the survivability of each component. The capability of these components may actually be better than the available test data suggests because the parts are usually tested to program requirements rather than to the hardware limits. However, the preliminary analysis suggests that capability variations exist between components of different "lots." This could indicate that some components are less capable than historical data predicts. To complicate matters, components may also have dose rate dependency.

Historical data on the components have been used so far in preliminary performance estimates and to estimate mass of shielding. The Europa Orbiter project requires lot verification after the components are procured and the shielding analysis will be updated based on the results of the Radiation Lot Acceptance Tests (RLAT). Testing for dose rate dependence is also required for some device types.

Several factors need to be considered when selecting components for space applications. The principle criteria used are the components' susceptibility to ionizing dose and to high-energy particles. The most current natural space environment models are used to determine if the components are flight worthy.

Because all high-energy particles cannot be completely shielded, parts must be selected that can survive and maintain performance through the bombardment of these particles. Components are checked for SEE characteristics using particle accelerator testing and a threshold is established where an upset or a destructive latch-up will occur. Most SEUs can be cleared autonomously with fault-tolerant designs; in some cases a complete power-on-reset is needed. An overall SEE analysis must be developed using the candidate components in the particular system mechanization to demonstrate compliance to the equipment specification.

Survivability and performance in a TID environment are typically tested with a gamma ray source, and the observed effect in a susceptible component is a permanent change in the operating characteristics. Parts may behave differently in the more convenient high dose rate of the test environment than in the lower dose rates of nominal space missions. The environment in Europa orbit will be a relatively high dose rate by spacecraft design standards and some component types will need to be tested for dose rate sensitivity. The selection of components for TID tolerance is closely linked to the system shielding design and is validated by performing worst-case circuit and system performance analyses.

### **Attitude Sensor Radiation Hardness**

The Europa IMU must survive and operate in one of the most extreme environments in the Solar System. The Europa Orbiter ACS consists of a suite of inertial sensors including a Stellar Reference Unit (SRU), a Sun Sensor Assembly (SSA), and an IMU. The Europa Orbiter will depend on gyros alone for attitude information upon EOI, because the optical sensors may not meet performance requirements in the worst case temporal variations in the natural space environment that surrounds the Jovian moon. The SRU technology is expected to have significant image degradation in high flux environments such as this.

The IMU design must tolerate the SEEs and TID of the Jovian environment. Among the methods for improving the radiation hardness of space equipment are the standard brute force techniques of adding shielding and replacing susceptible components with ones that are immune or less susceptible to this environment. If the opportunity exists, early integration of these requirements into the equipment design allows for optimization through part selection and part placement that can reduce the overall size, mass, and power. Ultimately, the feasibility of a particular sensor in this environment is determined by the inherent hardness of the sensing mechanism, the complexity and criticality of the associated sensor electronics, and the core sensor/electronics size that will scale the mass of shielding.

Total dose hardness is achieved in the hemispherical resonator gyroscope more readily than in an optical device due to the inherent hardness of the sensing element. The HRG utilizes synthetic fused silica whose key physical properties are known to change imperceptibly in high-dose gamma ray testing. SEEs may be postulated for the HRG readout in the form of transient charge deposition and voltage response in the pickoff circuits, but do not alter (offset) the underlying attitude data because the instrument possesses inherent "mechanical storage of angle" in the sensing mechanism. In other words, the standing-wave that provides the measure of angular input also preserves the information during short periods (as much as tens of seconds) when the readout and control electronics are not active. The stored angular momentum in the device, like a floated spinning mass, yields a relatively long time constant of decay of the sensor's capability with no applied excitation. Therefore, the very small single event transient (SET) disturbances may be minimized through signal processing techniques and virtually no error is incurred in the attitude reference.

## **CONCEPTUAL DESIGN STUDY FOR THE EUROPA IMU**

After the original announcement of the opportunity for the Europa IMU hardware, JPL found few vendors interested in pursuing hardware development for the extreme natural space environment requirement. A study-phase effort was appropriate to reduce risk for follow-on hardware development. For a unique and difficult mission such as that of the Europa Orbiter, the study-phase approach is a means of overcoming the barrier of development risk for potential suppliers. A competitive process awarded Litton a contract to study the feasibility of meeting the Europa mission requirements with HRG technology.

The conceptual design study focused on identifying and mitigating risk in surviving and operating the IMU in the Jovian environment. The effort involved the assessment of Litton's heritage SIRU™ product and identifying changes recommended to meet a broad set of Europa requirements. JPL defined three options to be examined:

1. The heritage SIRU™ with 130Y HRGs (nominally rated for the 100 krad TID environment)
2. The heritage SIRU™ with minor modifications to meet the Europa natural space radiation environment
3. The heritage SIRU™ with more extensive changes to meet all of the Europa requirements.

Litton, supported by Science Applications International Corporation (SAIC), performed the survivability and shielding analyses for these three options. The first option, proven for 100 krad(Si) missions, did not have positive design margin in some components, largely due to the Europa dose-depth penetration of the existing SIRU™ chassis. Therefore, this option was not considered beyond the initial survivability evaluation. Shielding analysis and part tolerance data showed that the heritage SIRU™ with added shielding and some part substitutions (option 2) is viable from a

survivability standpoint. The Europa IMU study contract coincided with the emergence of Litton's Scalable SIRU™ concept, which includes several breakthrough design elements favorable to more optimally meeting all of the Europa requirements. Scalable SIRU™ became option 3 in the study.

Among the breakthroughs associated with Scalable SIRU™ are the principal advances of smaller size and improved performance.<sup>7</sup> Smaller size translates into lower shielding mass and the improved performance allows operation without gyro heaters, reducing power dissipation. The shielding design and parts list for Scalable SIRU™ were carefully coordinated with the Europa IMU requirements to assure survivability. Many other features associated with the concurrent development of the Scalable SIRU™ and Europa IMU proved to be a benefit for this mission. Opportunities to optimize the design for radiation hardness, to tailor interfaces, to benefit from advancements in gyro performance, and to improve ground handling through the immunity to helium, are all significant advantages of the Scalable SIRU™.

Several key analyses were completed to allow a selection between the two feasible options:

- Detailed worst-case end of life electronics and sensor performance analysis
- Margins for electronics performance in the Europa natural space radiation environment
- Size and mass studies
- Preliminary single events effects analyses

The Europa IMU radiation hardness design studies as part of the overall conceptual design study are key to the trade-off analyses for the mission. Significant size, mass, and performance risk penalties would result from inaccurate modeling of the effects of natural space radiation on the IMU candidates. By adequately considering natural space radiation early in the conceptual study as integral to the design team effort, an optimized design solution can be achieved that maximizes performance while assuring survivability. Adopting an approach that combines shielding with part substitution, and conservative circuit tolerances for part parameter deratings, provides a solution with margin for environmental uncertainties and potential for even more severe missions. An example of which would be an extended mission at Europa. Establishing positive design margins for performance in the natural space radiation environment is a key to successful missions, as proven on Voyager and Galileo.

Analysis results indicated that Europa performance requirements alone could be met with both SIRU™ and Scalable SIRU™ options. However gyro heater control would not be required for the Scalable SIRU™ option due to the improved performance of the second-generation design. This, and other improvements detailed in the next section, made the Scalable SIRU™ option significantly more attractive from a combination of power consumption, size, performance, handling, and design

adaptability. During the Europa IMU study, the Scalable SIRU™ electronics design went through a preliminary board layout. Component locations were chosen to optimize shielding from structural elements of the IMU box enclosure.

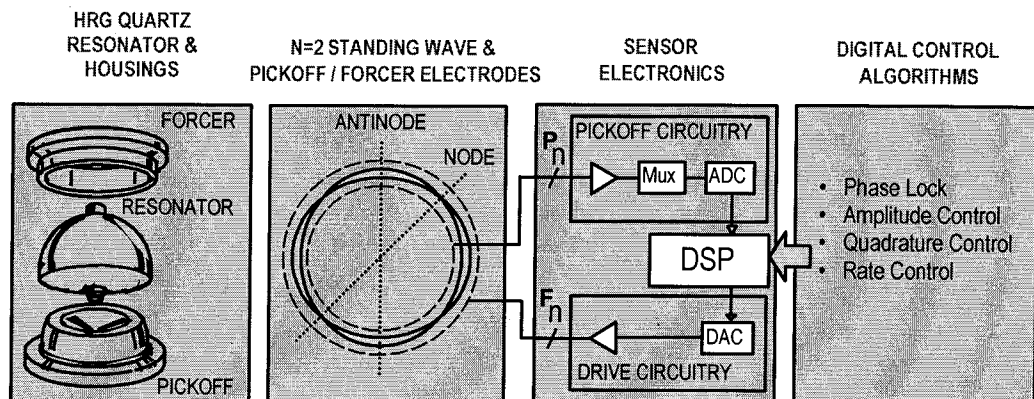
As a result of the design study, the Scalable SIRU™ is the baseline for the Europa IMU, taking advantage of the concurrent development program at Litton. There are a number of design requirements that have flowed down on Europa that are addressed as variants from the baseline Scalable SIRU™ configuration. Development risk is mitigated as each of these Europa-specific features can be designed into the baseline scalable design. The Scalable SIRU™ development has been underway almost a year ahead of the start of the Europa IMU hardware development program.

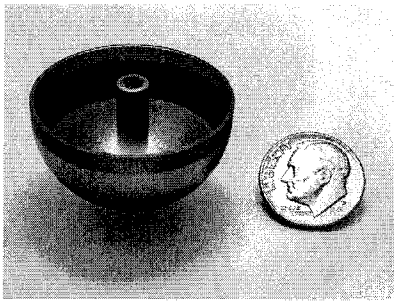
## HEMISPHERICAL RESONATOR GYROSCOPE TECHNOLOGY

Litton's HRG technology has been proven by over 1 million operating hours in space without any IMU failures and is providing continuous-on attitude reference data on 26 missions today. Some of the applications of HRG technology to date include:

- NASA's NEAR, Cassini, TDRS, EO-1, EOS, ICESat, and GALEX spacecraft
- Lockheed Martin's A2100 satellites, and others including Ikonos
- Boeing's 702 & other satellites

The current space-qualified HRG 130Y sensor (30 mm resonator diameter) is in its seventh production year and has been packaged and flown in several configurations of the first-generation SIRU™. These units are unique in providing ultra-high reliability and long life for medium and high-performance inertial sensing requirements.





**Figure 5. HRG Basic Implementation**

The HRG is a Coriolis vibratory gyro whose principle of operation is based on the rotation-induced precession of a standing-wave vibration mode of the fused silica resonator. In brief, the HRG control electronics establish a fixed-amplitude flexing mode vibration and measure the force required to oppose the tendency of the standing wave to precess relative to the case when the instrument is rotated. The control and readout for each gyro is accomplished by the closure of four relatively simple control loops (illustrated in Figure 5).

A brief history of the development of the HRG starts with the reduction to practice of the "sonic" gyro by General Motors in the mid-1960s. This novel instrument was based on the re-discovery of G.H. Bryan's 1890 article on the precession of standing waves on a wineglass-like structure.<sup>8</sup> The fit between space attitude reference system needs for pointing performance and reliability and the reduction of the HRG size to 30 mm in the early 1990s led to the first space flight of this technology in February 1996 aboard the NEAR spacecraft. The HRG today can be characterized as a mature instrument with a solid production base whose manufacturing processes and performance characteristics are well understood. At the same time, it is a technology that continues to realize new levels of performance and manufacturing efficiencies that are further broadening its base of applications.

Among the several modern methods for measuring inertial rotation, the HRG holds several advantages, including very high accuracy and stability in a small volume, low operating power, high reliability, and inherent radiation hardness. It is fair to draw an analogy between the HRG and the earlier, widely-used floated single degree of freedom spinning mass gyro. The two technologies utilize a Coriolis gyro principle of operation and both can achieve similar levels of inertial grade stability and precision pointing resolution in < 10 cubic inches (164 cc) volume per axis. Also, both possess the feature of "mechanical storage of angle," mentioned above in the context of providing accurate data across an upset or reset of the readout system. A discriminating characteristic for the HRG is the 10 million hour MTBF resulting from having virtually no wear-out mechanisms.

It is true that many modern gyroscope technologies operate at a performance limit based on the size of the sensing element. In fact, the HRG was once predicted to have performance vs. size limitations.<sup>9</sup> Through the significant achievements in

improved performance over the past few years, while simultaneously maintaining the current 30 mm resonator size, Litton has demonstrated that the performance achieved with this technology has not been limited by size.

### **Enhanced Performance Hemispherical Resonator Gyroscope**

The HRG performance achievements incorporated into the second-generation SIRU™ have been the result of advances in sensor construction and signal processing implementation.<sup>7</sup> A new version of the HRG is currently being released into production and is designated the HRG 130P ("Precision" performance). This gyro is the result of Litton's internal research and development efforts as well as technology development sponsorship from the US Government. The principal new features of the 130P HRG and corresponding enhanced sensor electronics include:

- A highly stable, symmetric mount for reduced temperature sensitivity
- An outer hermetic case, making the gyro impermeable to helium
- Improved electrode geometry for internal gain stability (predominantly scale factor accuracy)
- Differential pickoff and forcing capability for improved noise performance and channel isolation
- Pulse width modulated (PWM) drive signal generation for improved scale factor accuracy (predominantly linearity characteristics)
- Digital demodulation and filtering of pickoff signals for electronics simplification and improved noise performance

The Scalable SIRU™ product line and the Europa IMU take advantage of all of these enhanced HRG features through a combination of the benefits of positive performance margin over life, eased factory calibration effort, eased requirements for internal compensation processing, greater tolerance of challenging environments, and the option of less power by virtue of not using the thermal control heaters.

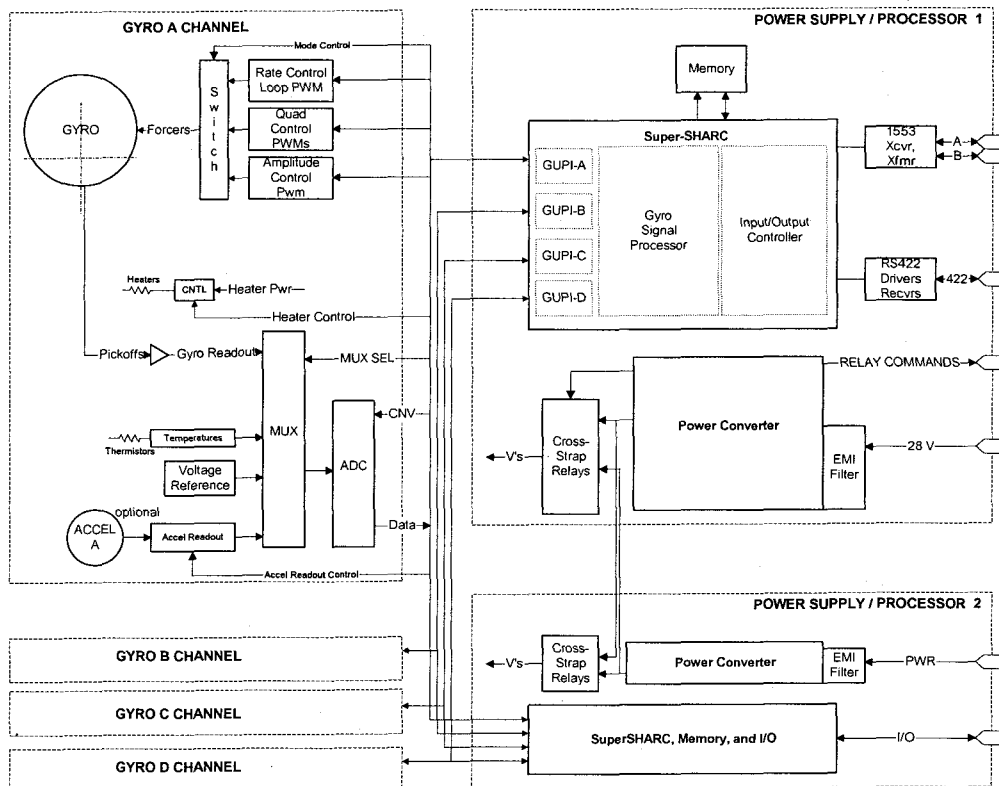
### **THE EUROPA ORBITER INERTIAL MEASUREMENT UNIT**

The Europa IMU incorporates concurrent breakthroughs in sensor electronics integration and performance improvements that allow the new product line, the Scalable SIRU™, to be adapted to a wider range of cost and performance requirements. The basic elements of the HRG-based space IMU are the individual gyros with preamp electronics integrated into the gyro assembly, accelerometers with integral hybrid electronics, analog circuitry for readout and drive signal conditioning, data conversion and sampling logic, a digital signal processor for control and readout computations, and a power converter to provide the standard analog and digital circuit supply voltages as

well as the -100 V resonator bias potential. A block diagram of the cross-strapped redundant Scalable SIRU™ mechanization is shown in Figure 6.

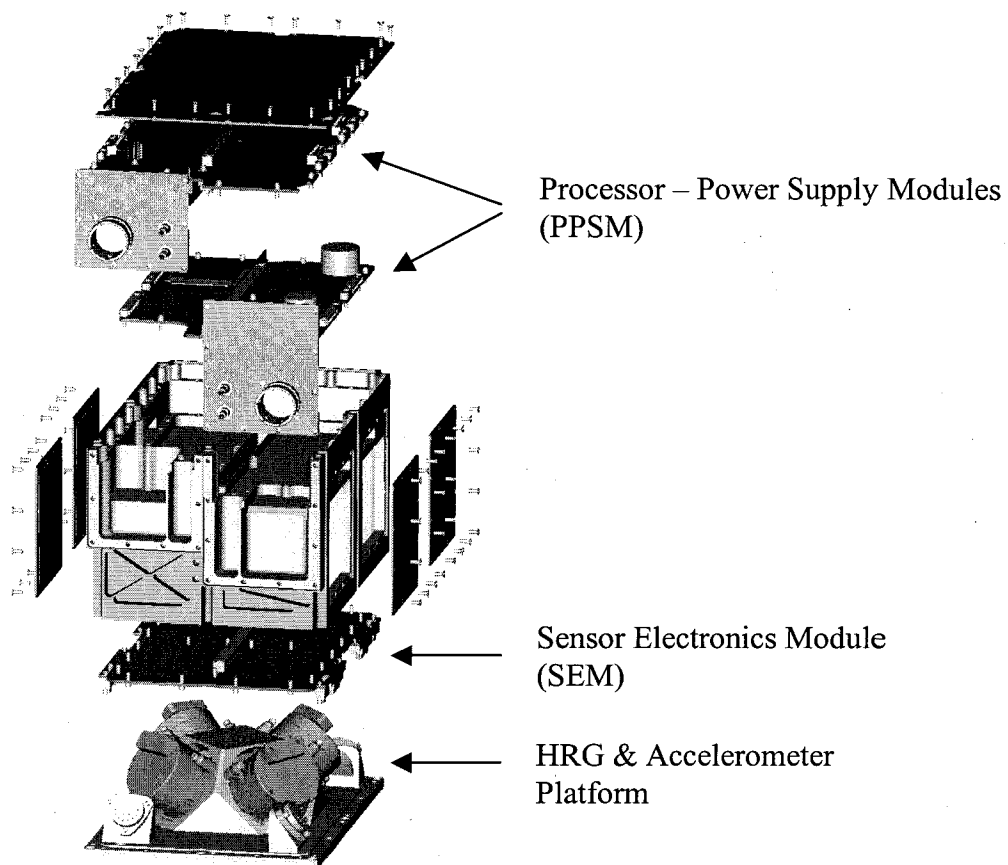
Many of the advantages of the Europa IMU concept and the Scalable SIRU™ system stem from the partitioning of the basic system elements, including

- Re-assignment of part of the sensor preamp signals to facilitate reduction of heating on the gyro assembly to < 40 mW, and allow twice the number of preamps to be used to obtain improved performance
- Shift in implementation to perform more of the readout and control signal processing in digital logic, including digital demodulation and filtering, and PWM generation of the precision drive signals. All of these result in fewer precision analog circuit components, improved noise and scale factor accuracy, and improved radiation hardness
- Integration of the first-generation SIRU™ chipset including a dual-DSP processor ASIC and individual gyro data conversion controller ASICs into a second-generation custom HRG DSP ASIC, with changes to the memory interface to reduce the number of RAM components. The current generation core SIRU™ cross-strapped redundant systems utilize two Space HRG & Accelerometer Readout/Control (SHARC) ASICs, four Gyro Unit Processor Interface (GUPI) ASICs, and eighteen 32kx8 RAMs. Scalable SIRU™ in the equivalent configuration uses only two Super-SHARC ASICs and two 32kx8 RAMs
- Consolidation of the processor and power converter modules, formerly four fault containment regions, into two Processor/Power Supply Modules (PPSMs)
- Elimination of a separate interconnect circuit card assembly by using stacking connector hardware. Overall, the number of connectors within the Scalable SIRU™ is reduced significantly



**Figure 6. Scalable SIRU™ System Mechanization Diagram**

The proposed design has redundant power supply and processor electronics, a set of four gyros in a pyramid configuration, and two thrust-axis accelerometers to meet the single fault tolerance requirement (Figure 7). In this configuration, any three of the four gyros can sense rotation in all three axes. A full Failure Modes Effects and Criticality Analysis (FMECA) will be performed on this design prior to the Preliminary Design Review (PDR). An alternate redundancy configuration exists in the form of two single-string (not internally redundant) units used in tandem to provide fault tolerance.



**Figure 7. Scalable SIRU™ Assembly**

One principal trade-off between the two fault tolerant approaches is the lower mass of the internally redundant unit vs. the response time of system reset during fault recovery or other configuration switching with a dual single string system. The required system reset of the internally redundant unit is just one factor in choosing the redundancy architecture. For Europa, the accelerometers are to be used for thrust monitoring of the bi-propellant engine and will be used intermittently for burn events. The issue of selecting the redundancy configuration is complicated by the fact that there are extended periods of time when the spacecraft is not being monitored, and the distance, which means that a radio signal can take as long as one hour (one way) to travel to the spacecraft. At the PDR, the Europa project will determine whether it will fly a single unit in this configuration or two units with only three gyros per IMU (Single String Scalable SIRU™). Table 1 summarizes this redundancy configuration trade space.

### **SuperSHARC Digital Signal Processor**

Litton's SuperSHARC processor is a key element of the electronics part integration that increases the shielding mass efficiency of the chosen Europa IMU configuration. As identified above, the SuperSHARC combines the functions of the

SIRU™ SHARC and GUPI chips. These very large-scale digital ASIC components are made with the Honeywell Solid State Electronics Corp. (SSEC) HX2000 radiation hard, silicon on insulator (SOI) process. The key functions and radiation hardness characteristics of the SuperSHARC are shown in Figure 8.

Using the SuperSHARC, the HRG and accelerometer readout is accomplished with a significantly reduced amount of analog signal conditioning electronics, a single analog-to-digital converter per gyro channel, and very few memory devices.

**Table 1**

**Trade Matrix of Cross-Strapped and Dual-Redundant Scalable SIRU™ Configurations**

Redundancy feature	Cross-Strapped (One internally-redundant IMU)	Dual-Redundant (Two single-string IMUs)
<b>Fault Containment Regions (FCR)</b>		
Power Supply & Processor (PPSM)	2	2 x 1
Gyro/Accel Channels	4	2 x 3
Total FCRs per shipset	6	8
<b>Subassemblies</b>		
PPSM	2	2 x 1
Sensor Electronics Module (SEM)	1	2 x 1
Gyro	4	2 x 3
Accel	2	2 x 1
Total Subassemblies per shipset	9	12
<b>Single Point Failures</b>	None	None
<b>Mass, baseline Scalable SIRU™</b>	7 kg	~12 kg
<b>Mass, with shielding for Europa</b>	11 kg	~18 kg
<b>Fault Management</b>	More complex	Less complex
<b>Dormant FCR Monitoring</b>	Requires system reset	No reset of primary FCRs
<b>Performance*</b>	73% worst-case, Pyramid platform	None, Orthogonal platform

\*Geometric dilution of precision (GDOP)

## Europa IMU Performance Margin

In addition to the above packaging improvements, the Europa IMU can take advantage of the Enhanced HRG performance margin, particularly the lower temperature sensitivity, by saving up to 8 W through the option for no gyro thermal control. The magnitude of the HRG 130P linear temperature sensitivity, which is on the order of 0.001-0.002 deg/hr/°C, and the improved repeatability across thermal cycles (hysteresis) on the order of 0.0001 deg/hr/delta-°C exhibited in the 130P, allow the Europa IMU to achieve all of its performance requirements without engaging the individual gyro thermal control. The individual gyro and voltage reference thermal control would typically be used only on the missions requiring performance beyond that of the current generation moderate to high accuracy SIRU™. The range of capability

from the basic performance to precision performance Scalable SIRU™ options is shown in the Appendix.

<p><i>Functions</i></p> <ul style="list-style-type: none"> <li>▪ 8 MIPS 24-bit fixed-point arithmetic DSP, Gyro Signal Processor (GSP)</li> <li>▪ 8 MIPS 16-bit Input/Output Controller (IOC)</li> <li>▪ Encoder / decoders for a single MIL-STD-1553 interface</li> <li>▪ Asynchronous &amp; synchronous RS422 serial interfaces</li> <li>▪ 4 Internal Gyro Processor Interfaces (GPI) <ul style="list-style-type: none"> <li>○ ADC sampling control and digital filtering</li> <li>○ PWM control</li> </ul> </li> <li>▪ Memory Interface Controller (MIC)</li> <li>▪ EDAC on external RAM</li> <li>▪ Internal GSP RAM</li> <li>▪ Internal GSP and IOC ROM</li> </ul>
<p><i>Radiation Hardness</i></p> <ul style="list-style-type: none"> <li>▪ Total dose hardness to <math>10^6</math> rad (Si)</li> <li>▪ No latch-up</li> <li>▪ Single Event Upset (SEU) hardness to <math>10^{-8}</math> error/bit/day</li> <li>▪ Prompt dose upset level to <math>10^{10}</math> rad (Si)/sec</li> <li>▪ Prompt dose survivability to <math>10^{12}</math> rad (Si)/sec</li> <li>▪ Neutron hardness to <math>10^{14}</math> particles/cm<sup>2</sup></li> </ul>

**Figure 8. Key Functions and Characteristics of the SuperSHARC ASIC**

## Europa Variant of the Core Scalable SIRU™ Design

The Litton HRG inertial reference units are “scalable” with respect to cost and performance attributes based on the choice of available design options and the extent of factory calibration and performance testing. The mission criticality of the Europa IMU, the challenging Jovian natural space radiation environment, and related constraints on size, mass, and power, drive the selection of a set of features added to or chosen from the baseline Scalable SIRU™ trade space. Table 2 shows the Europa IMU configuration among the key Scalable SIRU™ design options.

The directives and environments for the Europa mission hardware add a number of unique requirements to the original notion of an IMU product line of “mission compliant” hardware for typical Earth-orbiting and interplanetary spacecraft. The Europa program unique requirements include a full S-level parts program, 200 krad(Si) TID component hardness, 100% RLAT requirement for all ICs, Extreme Low Dose Rate (ELDR) test requirement for all bipolar devices, and additional radiation shielding according to a dose-depth curve indicating approximately 10 Mrad(Si) TID inside the

spacecraft electronics section panels. In addition, the Europa IMU has a unique requirement of a 3.3 V variant of the Mil-Std-1553 interface.

**Table 2**

**Matrix of Principle Scalable SIRU™ Configurations**

DESIGN FEATURES	Scalable SIRU™ Options	Europa IMU
Performance	Basic, Moderate, Precision	Basic
Input Voltage	28, 50, or 70 V	28 V
Thermal Control	None, Gyro heaters, Precision voltage reference heaters	None
Data Interface	1553, Async 422, Sync 422	Async 422, LVD 1553
Radiation Tolerance (TID)	100 krad, 4 Mrad	4 Mrad
Component Quality Level	PSAP, S	S
Redundancy Configuration	Cross-Strapped, Dual-Redundant	Cross-Strapped
Operational Flight Program	Download, PROM	PROM
Accelerometers	None, 2 Thrust-axis, 4 Skewed-axis	2 Thrust-axis

**Table 3**

**Europa IMU Shielding Added to the Core Scalable SIRU™ Chassis**

Additional Shields	Additional Mass	
	(lbs)	(kg)
Top Cover (1)	1.93	0.88
Access Covers (4)	1.69	0.76
Shield Plates (6)	5.40	2.50
<b>Total:</b>	<b>9.02</b>	<b>4.14</b>

The Europa IMU conceptual design study and subsequent program planning have proven nearly all of these unique requirements to be feasible within the framework of the Scalable SIRU™ program. The component radiation tolerance requirements have driven some part substitutions that are accommodated with alternate land pattern artwork on the Scalable SIRU™ printed wiring boards. The Europa design study and the current hardware development contract have come about in a timeframe where the Scalable SIRU™ product line design can be optimized (radiation-driven parts placement) and altered (part substitutions) to accommodate this new configuration.

Similarly, the design study identified plates made of tungsten-copper alloy W-10 (90% W, 10% Cu) to be used to provide the required additional shielding. These are factored into the core chassis elements by designing so that W-10 plates can be added to the minimum 80 mils (2 mm) aluminum faces of the IMU chassis, and that the top cover and side access covers can alternatively be made of W-10. The SEE environment and requirements have not driven unique features for the Europa IMU as these are critical characteristics even for lesser environments that Litton has addressed in the product line design. Using the above concurrent design shielding approach, the overall mass can be kept to within the specified 11 kg with little impact to the system assembly. Table 3 shows the Europa IMU shielding elements.

The Scalable SIRU™ design effort is underway and proceeding according to design requirements that encompass the Europa IMU requirements. The complement of Scalable SIRU™ engineering development units (EDUs) and qualification test unit as well as a Europa EDU and protoflight unit will provide for a high-confidence means of fully validating and qualifying the Europa-specific portions of the design.

## **CONCLUSION**

At the time of the announcement of opportunity for the Europa Orbiter mission there was a low degree of confidence that an IMU could be built to meet the requirements and goals of this mission, particularly within the given limitations of cost, mass, and schedule. The Europa spacecraft will be exposed to an extreme natural space radiation environment once it enters the inner Jovian system – an unthinkable 4 Mrad(Si) total dose environment, 40 times that typically specified for Earth orbit and interplanetary missions.

Litton and JPL collectively mitigated the initial risk of IMU hardware development for the Europa Orbiter by first completing a study contract. The goal of the study contract was to perform a joint evaluation of the Europa environments, design elements, and requirements while in a formative state, to yield a solution that broadly meets the mission requirements and goals. The study results showed that the heritage Core SIRU™ design, used on NEAR, Cassini, EO-1, and numerous other Earth-orbiting spacecraft to date, could satisfy the principal operational requirements with significant shielding and component substitutions. However, the SIRU™ was not optimal in light of the significant advances and concurrent development of the second-generation HRG system. The Scalable SIRU™ product provides an optimal solution that has the requisite reliability and environmental tolerance along with significant performance margin for the Europa Orbiter ACS within 11 kg and 22 W.

Litton's HRG technology as implemented in the Scalable SIRU™ is the unique attitude reference sensor to offer reliable continuous operation with very high accuracy in severe natural space radiation environments. A hardware contract has been awarded and will produce an IMU capable of providing attitude data in all mission phases, including the critical orbit insertion during the peak natural space radiation

environment. The Europa IMU, in combination with the advancements made with the X2000 program, will enable the Europa Orbiter and other upcoming missions to reach and operate in the most inaccessible areas of our Solar System.

## ACKNOWLEDGEMENT

The authors wish to acknowledge John Retzler of SAIC for the voluminous analyses of IMU design for radiation hardness, and recognize Jennie Johannesen, Dr. Martin Ratliff and Stephen Brewster of JPL, and Frank Landavazo and Susan Schorr of Litton for contributions to the paper and presentation materials. This research was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration.

## ACRONYMS

ACS	Attitude Control Subsystem
ASIC	Application-Specific Integrated Circuit
EDU	Engineering Development Unit
EOI	Europa Orbit Insertion
ELDR	Extreme Low Dose Rate
FCR	Fault Containment Region
FMECA	Failure Mode Effects and Criticality Analysis
GCR	Galactic Cosmic Ray
GDOP	Geometric Dilution of Precision
GUPI	Gyro Unit Processor Interface
HRG	Hemispherical Resonator Gyroscope
IMU	Inertial Measurement Unit
JOI	Jupiter Orbit Insertion
LET	Linear Energy Transfer
MTBF	Mean Time Between Failure
PDR	Preliminary Design Review
PPSM	Power Supply & Processor Module
PSAP	Part Supplier Approval Process
PWM	Pulse Width Modulation
RLAT	Radiation Lot Acceptance Test
SEE	Single Event Effects
SEM	Sensor Electronics Module
SET	Single Event Transient
SEU	Single Event Upset
SHARC	Space HRG & Accelerometer Readout Controller
SIRU™	Space Inertial Reference Unit
SOI	Silicon on Insulator
SRU	Stellar Reference Unit
SSA	Sun Sensor Assembly
TID	Total Ionizing Dose

## REFERENCES

1. Wright, D., Bunke, D., "The HRG as Applied to a Satellite Attitude Reference System," Paper No. AAS 94-004, AAS Guidance and Control Conference, Keystone, CO, February 1994
2. Maddock, R. W., et al., "The Outer Planets / Solar Probe Project:: *Between an Ocean, a Rock, and a Hot Place*," IEEE Aerospace Conference, Aspen, CO, March 1999, Proceedings. Vol. 1 (A99-43255 12-31), p. 383-402
3. Johannesen, J. R., D'Amario L. A., "Europa Orbiter Mission Trajectory Design," AAS Paper 99-360, AAS/AIAA Astrodynamics Conference, Girdwood, AK, August 1999, Proceedings Vol. 103 (A00-35032 09-12), p. 895-908
4. Johnson, T. V., Chyba, C., Klaasen, K. P., Terrile, R. J., "Outer Planets/Solar Probe Project - Europa Orbiter," Lunar and Planetary Science Conference, Houston, TX, March 1999, Proceedings (A00-47001 13-91)
5. Price, H. W., et al., "X2000 Flight Missions Utilizing Common Modular Components," IEEE Aerospace Conference, Aspen, CO, March 1998, Proceedings. Vol. 2 (A98-34433 09-31), p. 369-381
6. Devine, N., Garrett, H. B., "Charged Particle Distributions in Jupiter's Magnetosphere," Journal of Geophysical Research, Vol. 88 No. A9, p. 6889-6903, September 1983
7. Johnson, G., Lefley, A., Toole, P., "Development of the HRG Based Scalable Space Inertial Reference Unit for Long-Life Moderate and Precision Pointing Spacecraft," Paper No. AAS 01-034, AAS Guidance and Control Conference, Breckenridge, CO, February 2001
8. Bryan, G. H., "On the Beats in the Vibrations of a Revolving Cylinder or Bell," Cambridge Phil. Soc., Vol. VII, p. 101, 1890
9. Loper E.J., Lynch, D.D., Stevenson, K.M., "Projected Performance of Smaller Hemispherical Resonator Gyros," Presented at the Position Location and Navigation Symposium (PLANS '86), November 1986

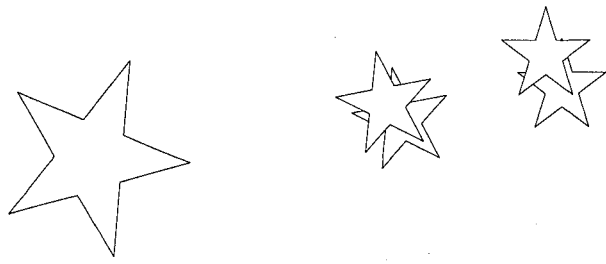
## APPENDIX

The key Scalable SIRU™ performance specifications for the cross-strapped internally redundant IMU configuration are given in Table A - 1.

**Table A - 1**

### Scalable SIRU™ Product Line Performance Specifications

PARAMETER	Basic Performance	Precision Performance
<b>GYRO PERFORMANCE</b>		
<b>Rate Range</b>		
Full performance, °/s	± 10	± 4
Reduced Performance, °/s	± 300	± 300
<b>Scale Factor</b>		
Nominal 1553, arc-sec/LSB	0.05 (1553)	0.05 (1553)
Nominal Async RS422, arc-sec/LSB	0.05/64	0.05/64
Nominal Sync RS422, nano-radian/LSB	1	1
Stability, Short Term, ppm 1σ	60 ppm 1hr uncertainty, ±8°C, 12-hr test	<1 ppm 1hr uncertainty, ±1°C, 12-hr test
Linearity, 1σ	30 ppm,  rates  1 °/s  0.108 °/hr  rates  < 1 °/s	1 ppm,  rates  1 °/s  0.004°/hr  rates  < 1 °/s
Stability, Long Term, % 3σ	0.5	0.5
<b>Bias</b>		
Stability, Short Term, °/hr 1σ	0.03 °/hr 1hr uncertainty, ±8°C, 12-hr test	0.0003 °/hr 20-min uncertainty ±0.1°C, 12-hr test
ASDR, °/hr/g	0.005	0.005
Magnetic Sensitive °/hr/gauss	0.002	0.002
Stability, Long Term, °/hr 3σ	1.3	1.3
<b>Noise</b>		
NEA, arc-sec pp	5 1800s, 20Hz	0.1 1800s, 20Hz
Angle White Noise, arc-sec/Hz <sup>1/2</sup>	0.009	0.0004
Angle Random Walk, °/hr <sup>1/2</sup>	0.0003	0.00006
<b>Maximum Bandwidth, Hz</b>	<25	<500
<b>Latency, milli-sec</b>	14.4	0.8 + ½ sample time
<b>Time Tag Accuracy, μsec</b>	±5	±5
<b>INTERFACE</b>		
Power (watts)	3 gyro operation 4 gyro operation Heaters (per gyro)	19 23 0.04 W/C
Input/Output	1553 / RS422	1553 / RS422



# ENABLING TECHNOLOGY FOR NASA'S EUROPA ORBITER MISSION

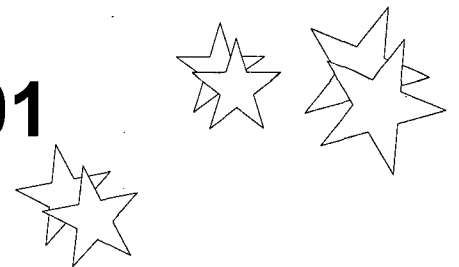
**Edward H. Konefat**

**Edward C. Litty**

**Scott K. Voigt**

**David S. Wright**

**Presented: February 01, 2001**

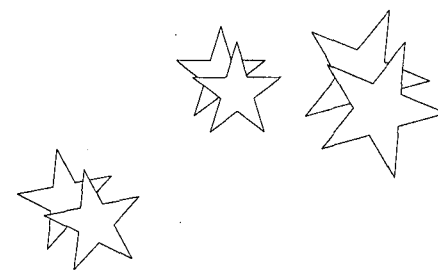


# Introduction

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- **Europa Mission is driving key technologies to be identified**
  - Significantly more time in the inner radiation belts of Jupiter than Voyager or Galileo
  - 4 Mrad(Si) behind 2.5 mm aluminum
- **IMU is the sole sensor in key parts of the mission such as Europa Orbit Insertion (EOI)**
- **Litton's HRG is found to be an enabling technology for the Europa Mission**



# Europa Orbiter Mission

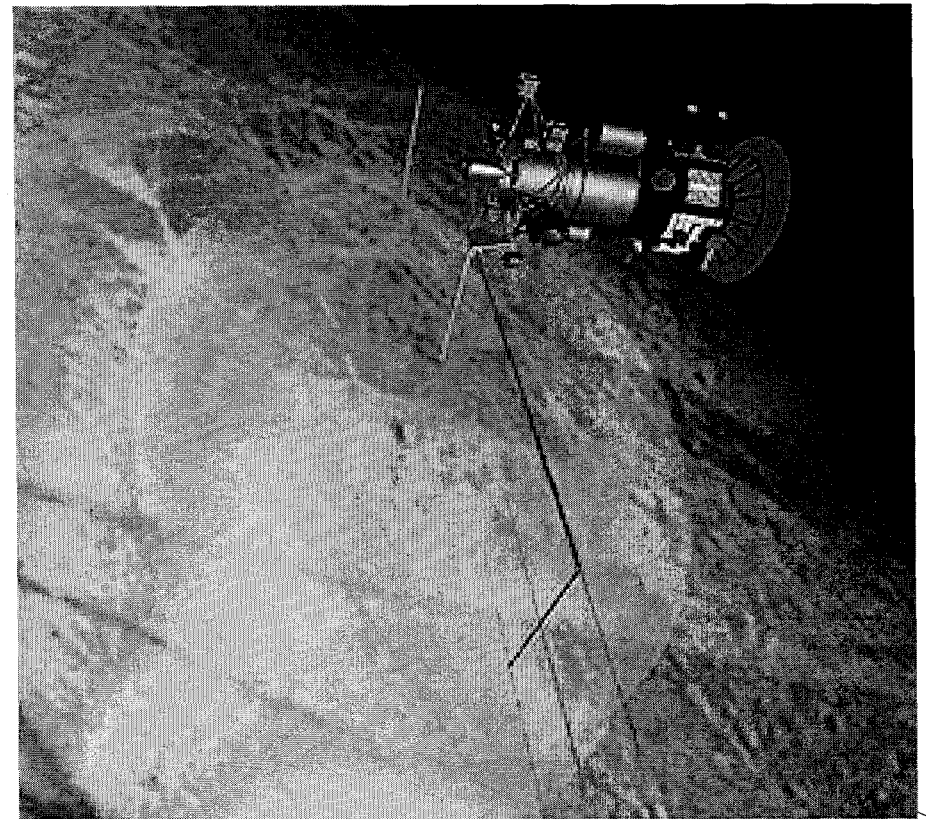
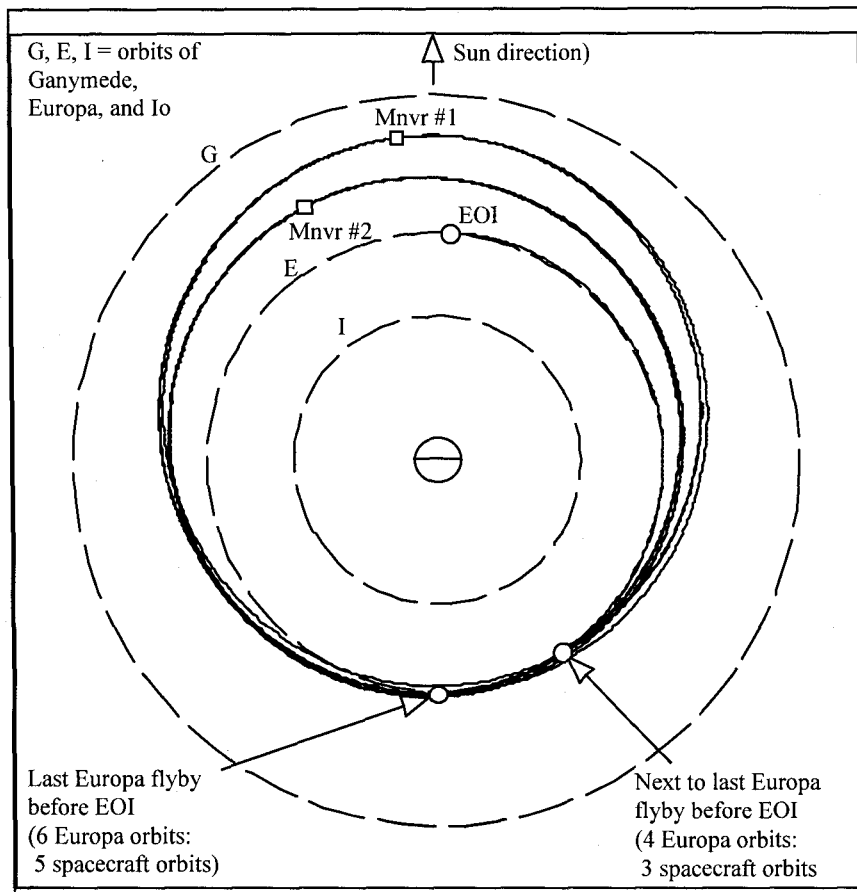
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- **First spacecraft to orbit the moon of another planet**
- **In search of subsurface ocean of liquid water**
- **Approximately four-year mission**
  - 3 year cruise and 1.5 year tour of Jupiter's satellites
  - 3 month “endgame” fly-bys of Europa
  - 30 days science in Europa orbit
- **Last series of fly-bys and Europa orbit are within the severe natural space radiation belts**
- **4 Mrad(Si) TID is accumulated in the last 4 months of the mission**



# Representative Trajectory at Europa Orbit Insertion (EOI)



# Europa Orbiter Mission Natural Space Environment

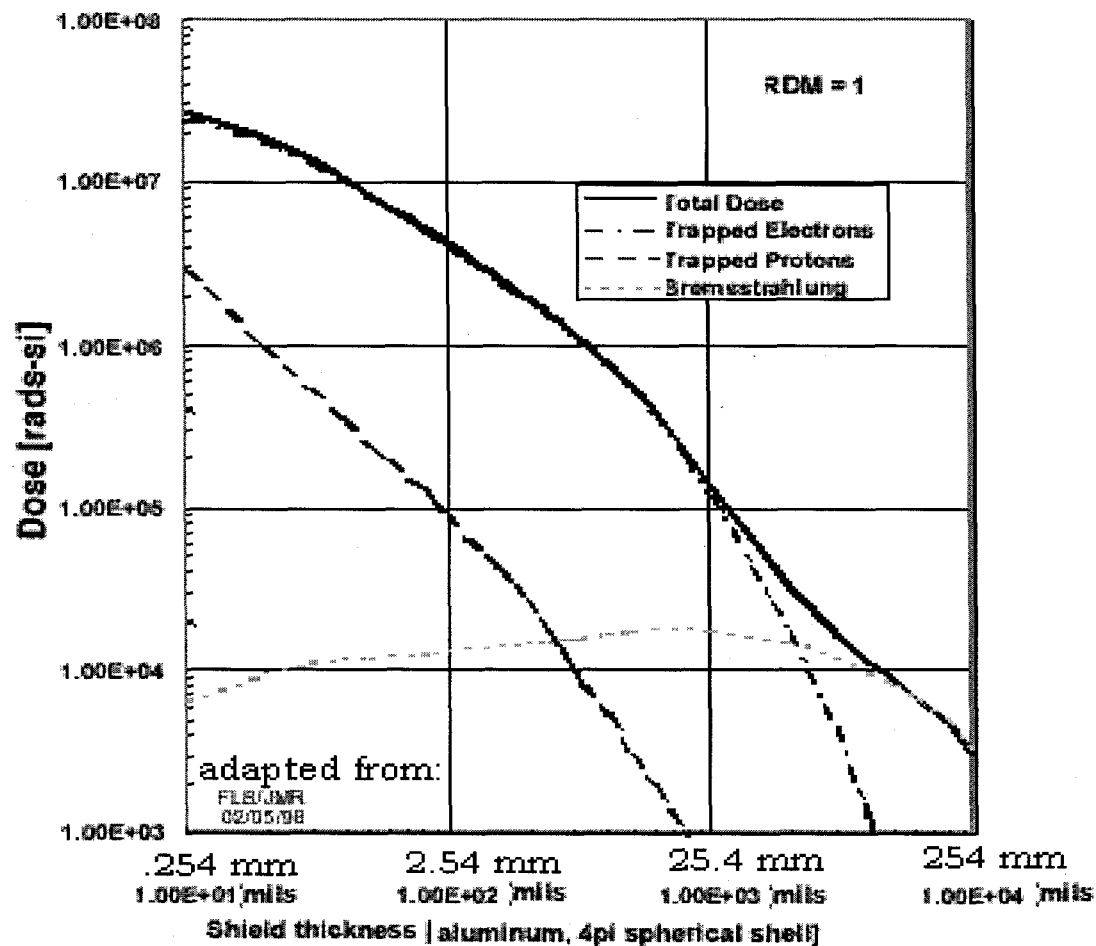
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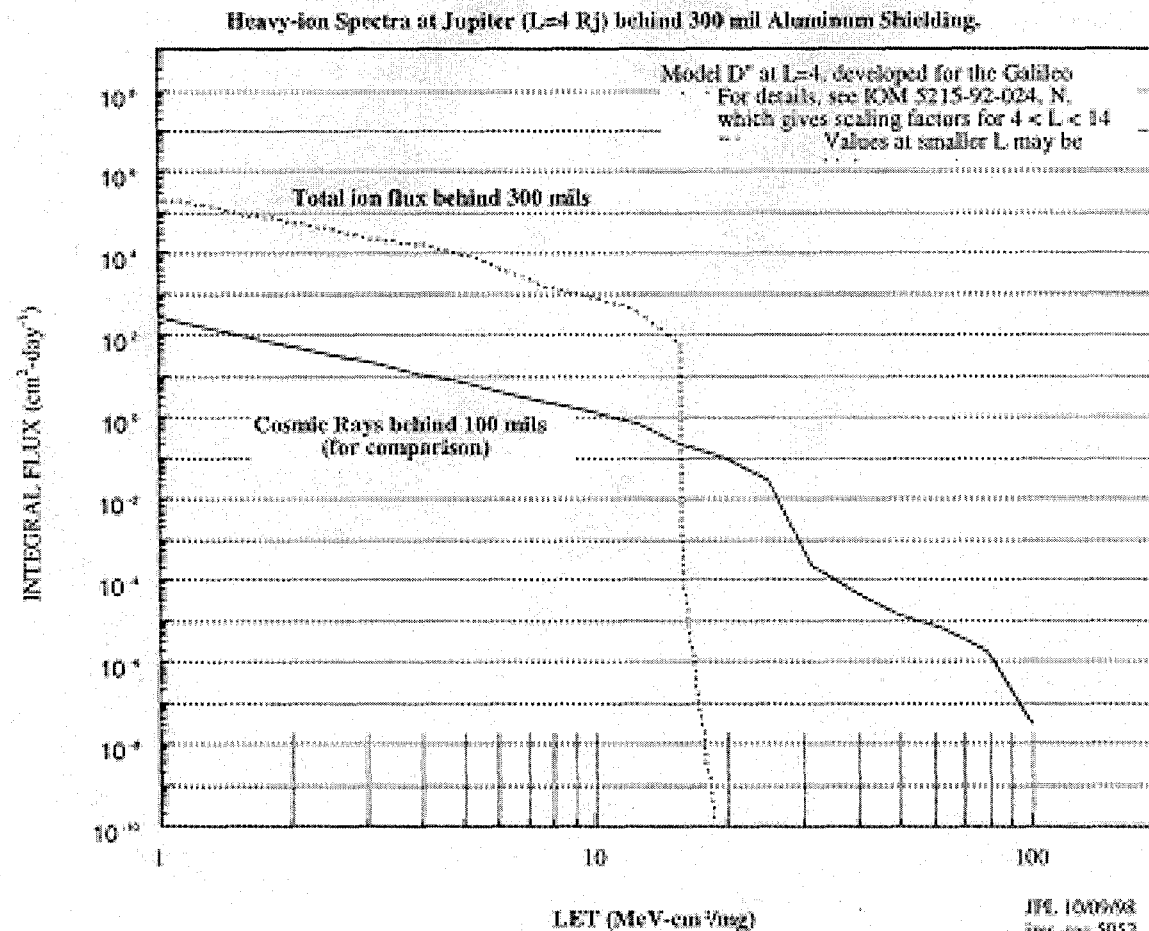
- **Total Ionizing Dose (electrons & protons)**
  - Low dose rate during cruise
  - High dose rate of electrons and protons within Jupiter's magnetosphere
  - 10 Mrad(Si) within electronics bay panels
  - 4 Mrad(Si) behind 2.5 mm aluminum
- **Single Event Effect producing particles**
  - Galactic Cosmic Ray background
  - Solar flares
  - Enhanced heavy ion particle environment within Jupiter's magnetosphere



# Dose Depth Curve for Europa Orbiter



# Heavy Ion Spectra for Inner Jovian System

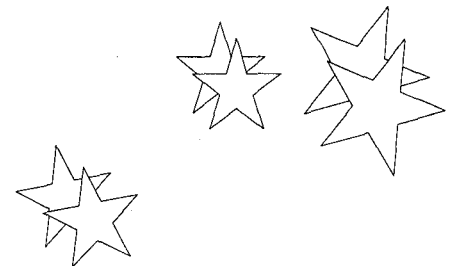


# Europa IMU Feasibility Study

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- **Initially high risk for suppliers to meet the combination of requirements**
- **Study phase approach adopted**
- **Litton was selected for a feasibility study of the HRG SIRU™ for the Europa mission**
  - Heritage SIRU™ with minor modification
  - Heritage design with more extensive modifications (Scalable SIRU™)



# Attitude Sensor Radiation Hardness

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- **HRG is an inherently radiation-hard sensor**
- **TID effects in the basic sensing element material known to be insignificant**
- **Readout and control electronics are readily hardened for natural space environment**
- **No SEE concerns**
  - No latch-up or single event upset issues
  - HRG has “mechanical storage of angle”
  - Small single event transient (SET) disturbances may be minimized through signal processing techniques



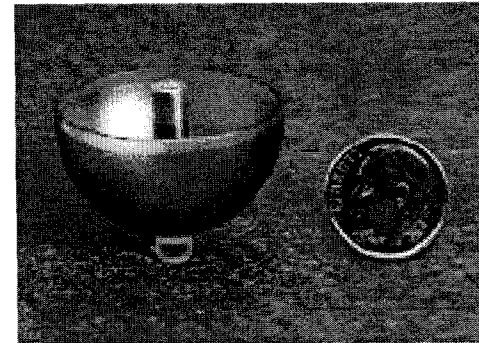
# Hemispherical Resonator Gyroscope

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- **G.H. Bryan's 1890 study of the precession of standing waves on bell structures**

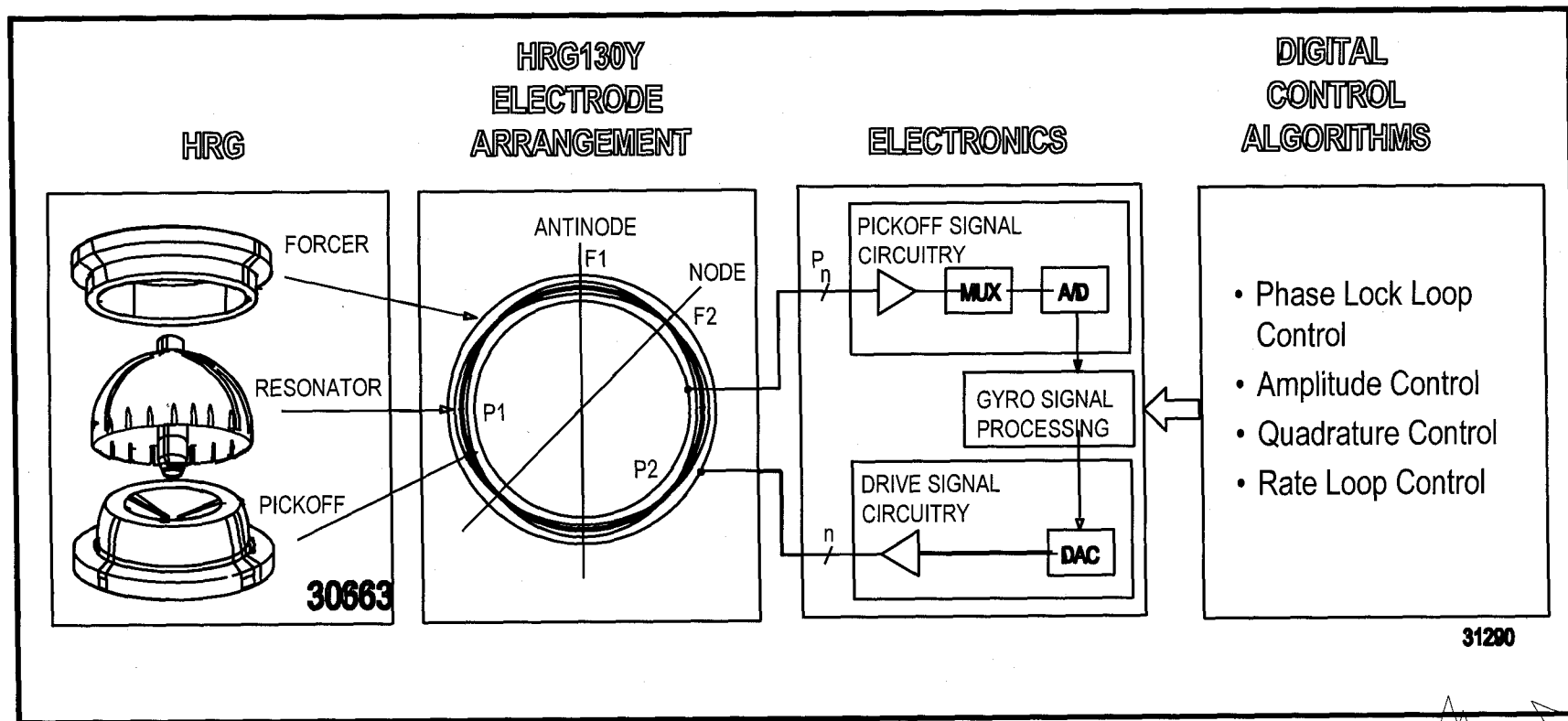
– 30 mm “Wineglass” gyro



- **Developed into high-accuracy, ultra-high reliability Coriolis vibratory gyro**
- **On-board 26 spacecraft including NASA's NEAR, Cassini, & EO-1**



# Hemispherical Resonator Gyroscope

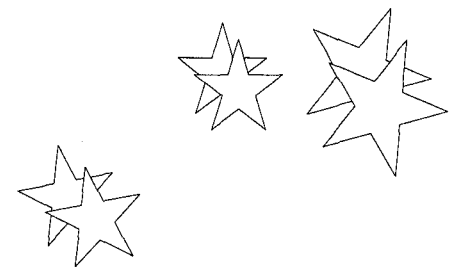


# Enhanced Performance Hemispherical Resonator Gyroscope

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- **New version of the HRG (130P)**
  - A highly stable, symmetric mount for reduced temperature sensitivity
  - An outer hermetic case, making the gyro impermeable to helium
  - Improved electrode geometry for internal gain stability (scale factor accuracy)

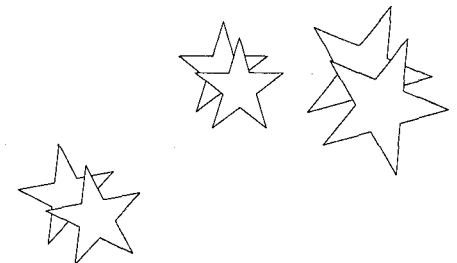


# Enhanced Performance Hemispherical Resonator Gyroscope (continued)

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- **Enhanced performance HRG electronics**
  - Lower-noise differential pick-off and forcing
  - Pulse width modulated (PWM) drive signal generation for improved scale factor linearity
  - Digital demodulation and filtering of pickoff signals for electronics simplification and improved noise performance



# The Europa Orbiter Inertial Measurement Unit

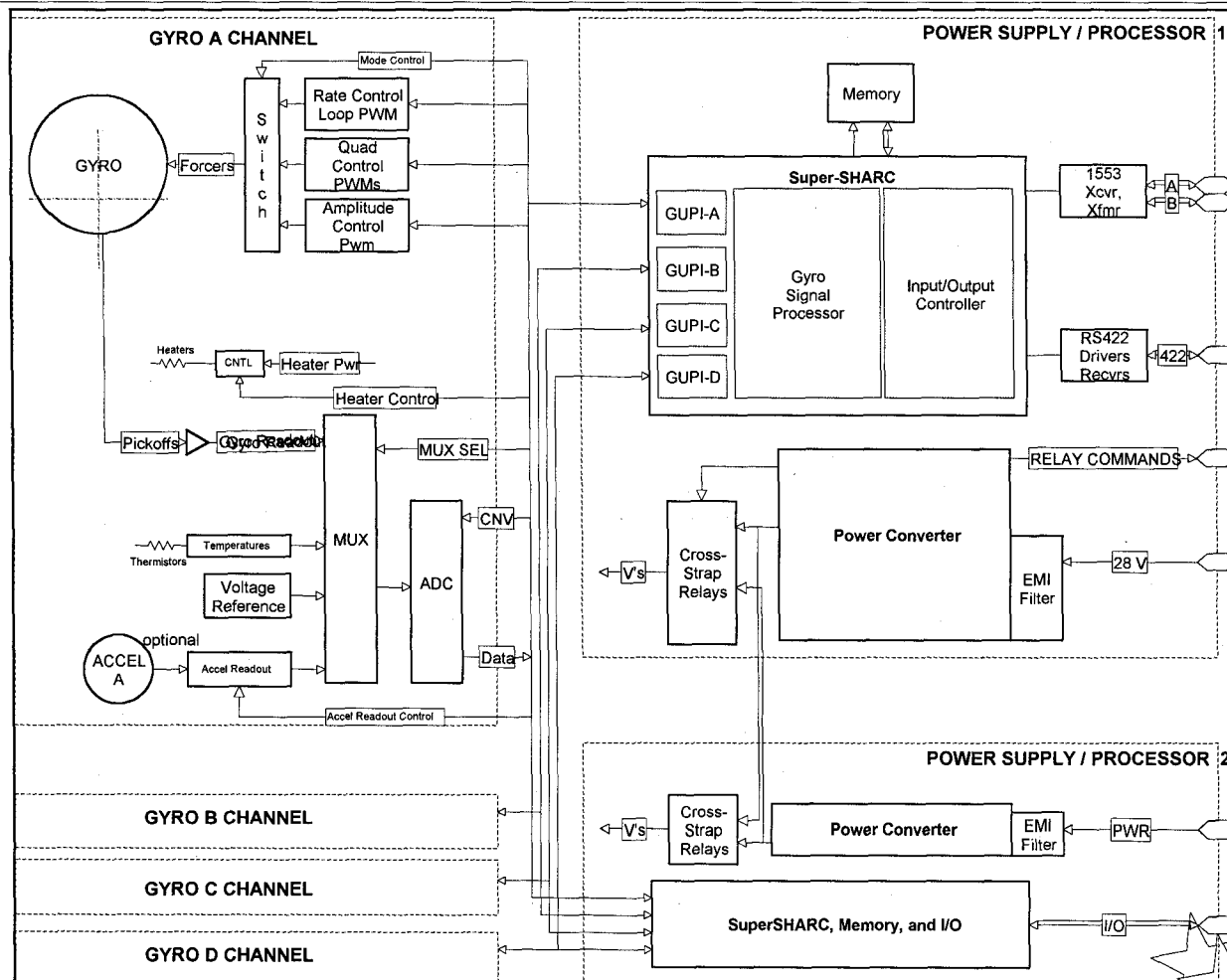
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- **Scalable SIRU™ chosen for Europa IMU**
- **Advantages over heritage system**
  - Lower shielding mass due to smaller package
    - SuperSHARC DSP
    - Reduced number of components, connectors, & circuit card assemblies
  - Concurrent product line development allows optimization for Europa mission requirements
  - Lower power due to gyro performance margin

# Scalable SIRU™

## System Mechanization Diagram



# Europa Orbiter Version of the Scalable SIRU™

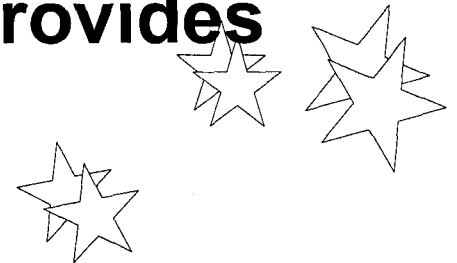
DESIGN FEATURES	Scalable SIRU Options	Europa IMU
Performance	Basic, Moderate, Precision	Basic
Input Voltage	28, 50, or 70 V	28 V
Thermal Control	None, Gyro heaters, Precision voltage reference heaters	None
Data Interface	1553, Async 422, Sync 422	Async 422, LVD 1553
Radiation Tolerance (TID)	100 krad, 10 Mrad	10 Mrad
Component Quality Level	PSAP, S	S
Redundancy Configuration	Cross -Strapped, Dual -Redundant	Cross -Strapped
Operational Flight Program	Download, PROM	PROM
Accelerometers	None, 2 Thrust -axis, 4 skewed -axis	2 Thrust -axis

# CONCLUSION

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- The radiation environment and equipment requirements for the Europa Orbiter ACS are very challenging
- Risk mitigation for Europa IMU development is achieved through a study phase contract and leveraging of Litton's concurrent development efforts
- The HRG in the Scalable SIRU™ provides a unique, optimal solution



# CONCLUSION

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***The Europa IMU, in combination with the advancements made with the X2000 program, will enable the Europa Orbiter and future missions to operate reliably in the most inaccessible and hostile environments of our Solar System***

